

Design Optimization of Piezoceramic Multilayer Actuators for Heavy Duty Diesel Engine Fuel Injectors

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**2013 Vehicle Technologies Annual Merit Review
and Peer Evaluation Meeting
Arlington, VA
May 14, 2013**

**Project ID #:
PM046**

*This presentation does not contain any proprietary,
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Overview

Timeline

- Start – Oct 2008
- Finish – Sept 2014

Budget

- Total project funding
 - DOE – \$1,390K
 - 2012 - \$300K
 - 2013 - \$190K (\$25K allocated to date)
 - Cummins - \$1,390K Cost Share (DOE CRADA)

Barriers*

- Changing internal combustion engine combustion regimes
 - Peak cylinder pressure
 - Fuel injection pressure
 - Fuel formulations
- Long lead times for materials commercialization

Target

- Advanced fuel injection system with pressures > 2800 bar
- 50% improvement in freight hauling efficiency by 2015

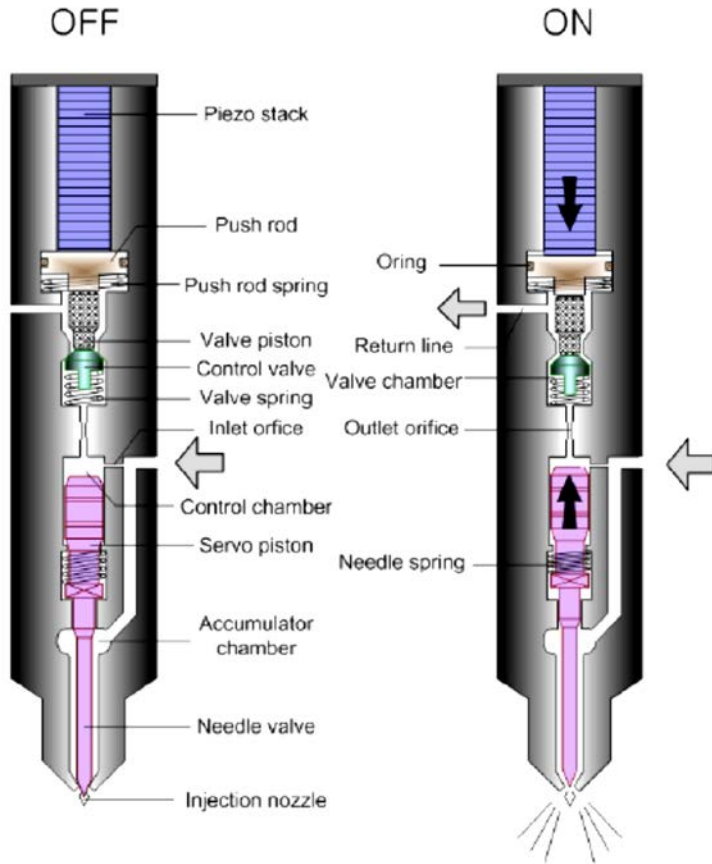
Partners

- Cummins, Inc.
- EPCOS
- Kinetic Ceramics, Inc.

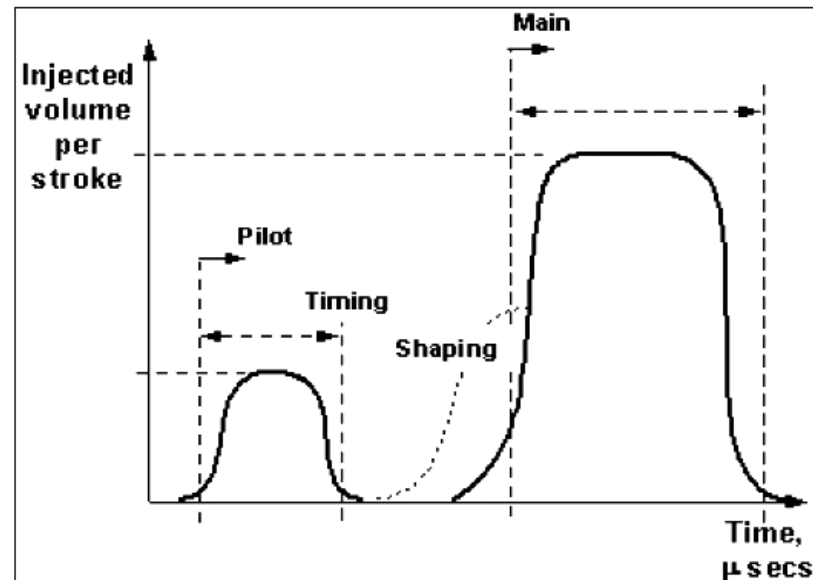


*Vehicle Technologies Program,
Multi-Year Program Plan, 2011-2015

Piezoactuation Enables Precise Rate Shaping and Control of Fuel Injection Timing and Quantity



- Spray control of solenoid fuel injectors is limited
- Piezo fuel injector can improve fuel efficiency and reduce NO_x emission and noise



Piezostack used in a fuel injector

(Kim et al, SAE 2005-01-0911)

Applied voltage: <200V; Frequency: 200Hz;
Displacement: 80 μm ; Force: 3000N;
Temperature: <150°C; Lifetime: 1 million miles

Objectives

- **Generate required mechanical data on PZT piezoceramics under working conditions equivalent to piezo fuel injector.**
- **Conduct fatigue and dielectric breakdown testing on actuator components.**
- **Characterize fatigue responses of PZTs with respect to the application in fuel injection system.**
- **Develop experimental approach to testing mechanical strength of PZT stacks.**
- **Use probability design sensitivity analysis with FEA to identify optimum design of PZT multilayer piezoactuator.**

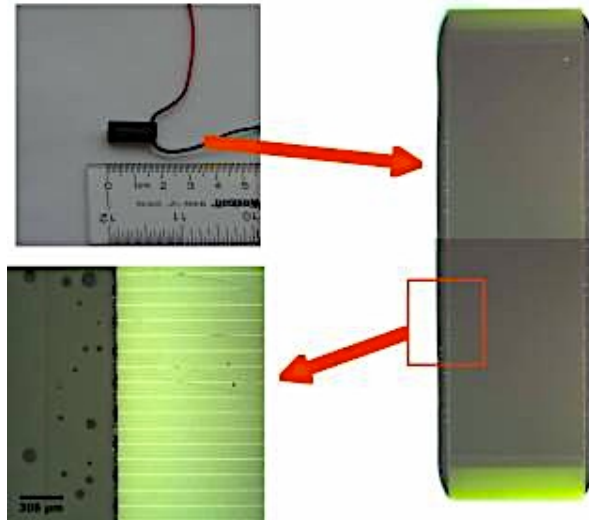
Milestones

- **Sept 2012: Environmental effect and fatigue study of identified PZT piezoceramics and stacks.**
- **Sept 2013: Effects of humidity and temperature (80% RH, 85°C) on the mechanical properties of PZT ceramics with and without applied electric field.**
- **Sept 2013: Study of thermal response and cyclic fatigue of short PZT stacks (typical of PZT plates consisting of 10-PZT layers) in cycling electric field.**

Approach

- **Measure and compare mechanical properties of PZT piezoceramics that are candidates for use in piezoactuators.**
- **Develop accelerated test methods that enable rapid and reliable qualification of piezoactuators.**
- **Measure response and reliability of piezoactuators and link to measured piezoceramic properties.**
- **Adapt to fuel injectors for Heavy Duty Diesel engines.**

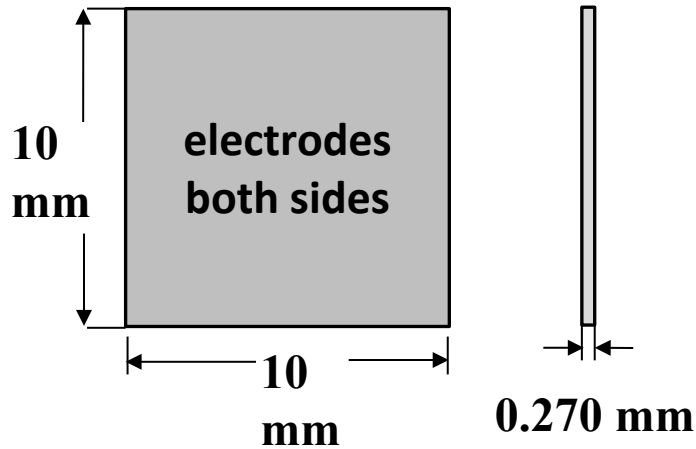
PMLAs have a complex multi-microlayers structure



PMLAs would be used inside a fuel injector

Accomplishments

Humidity Effect was Studied by Pretreating PZT Specimens in a Controlled Humidity Chamber



- A chamber with saturated KBr solution was used; relative humidity (RH) was maintained at 85% at room temperature.
- PSI (Piezo System Inc) 5A4E (10mmx10mmx0.267mm, electroded, and poled) specimens were treated in the chamber for a specified time.
- Ball-on-ring flexure testing used in evaluating the effect of humidity on the mechanical property under various electric conditions: OC and Ec.

Accomplishments (continued)

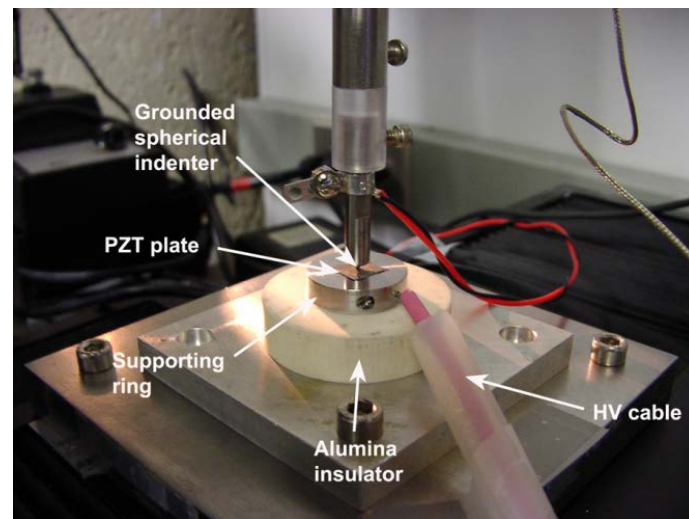
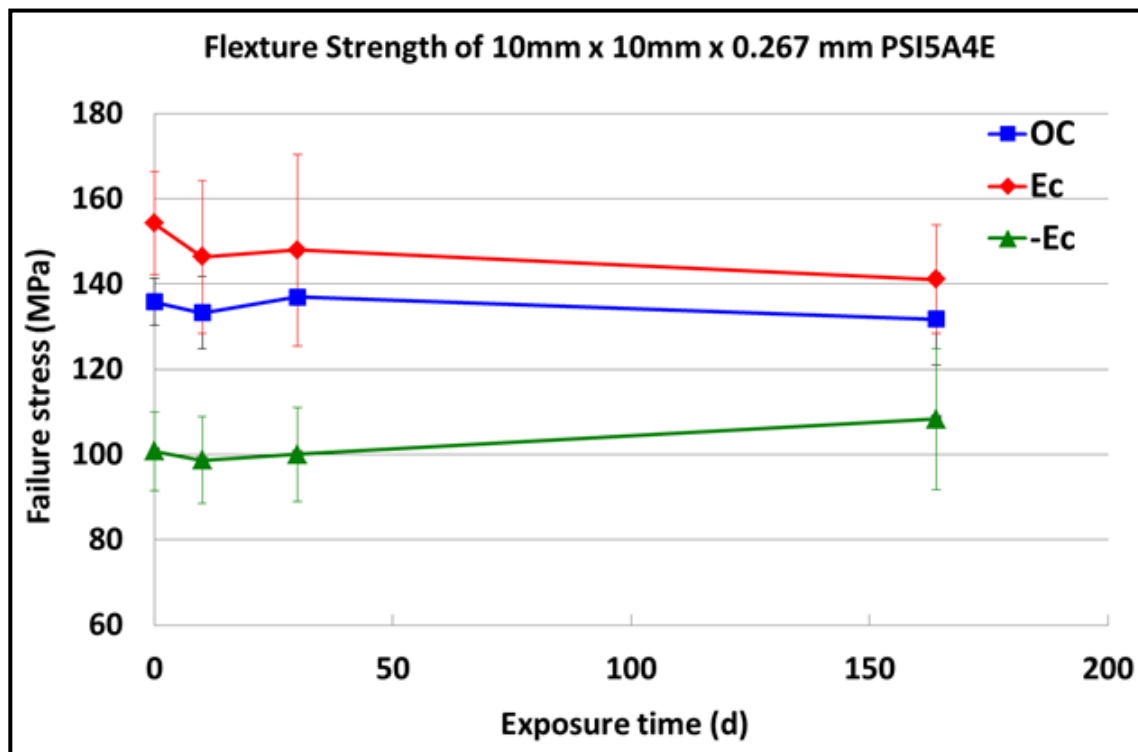
Strength Testing of 12 Groups of Pre-treated PZT Specimens

Date	Group #	Time (days)	Gain (mg)	E field	No. of Tests
2/14/12	1	0	N/A	OC	12
2/16/12	2	0	N/A	P (+1 Ec)	12
2/22/12	3	0	N/A	N (-1 Ec)	12
2/15/12	4	10	6	OC	12
2/16/12	5	10	5.5	P (+1 Ec)	11
2/22/12	6	10	3.5	N (-1 Ec)	13
3/5/12	7	30	1	OC	12
3/5/12	8	30	0.3	P (+1 Ec)	12
3/5/12	9	30	0.7	N (-1 Ec)	12
7/16/12	10	164	1	OC	13
7/16/12	11	164	1	P (+1 Ec)	13
7/16/12	12	164	1	N (-1 Ec)	10

- Selected specimens were put into the chamber on 2/3/12.
- OC: open circuit.
- P: +1Ec was applied parallel to specimens' polarization.
- N: - 1Ec was applied anti-parallel to specimens' polarization.

Accomplishments (continued)

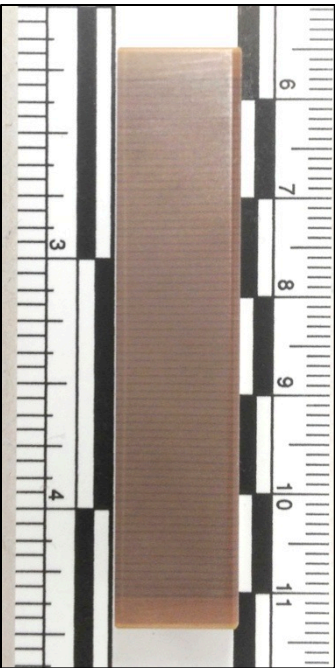
Humidity has a Little Effect on Mechanical Strength of PZT



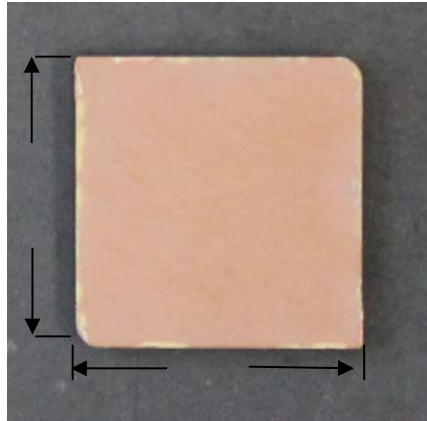
Ball-on-ring mechanical testing setup with applied electric field

Accomplishments (continued)

Custom Made BoR Fixture Developed for PZT High Temperature Strength Testing

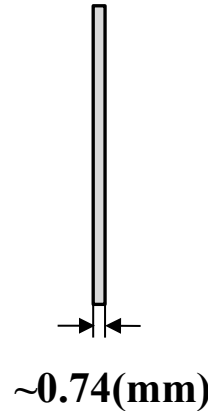


~12
(mm)

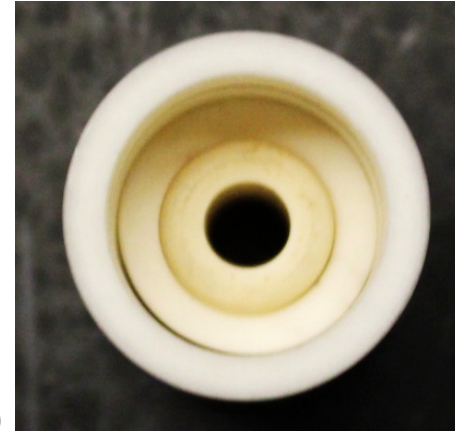


~12
(mm)

10-layers EPCOS PZT disks
extracted from 54 mm long stacks



~0.74 (mm)

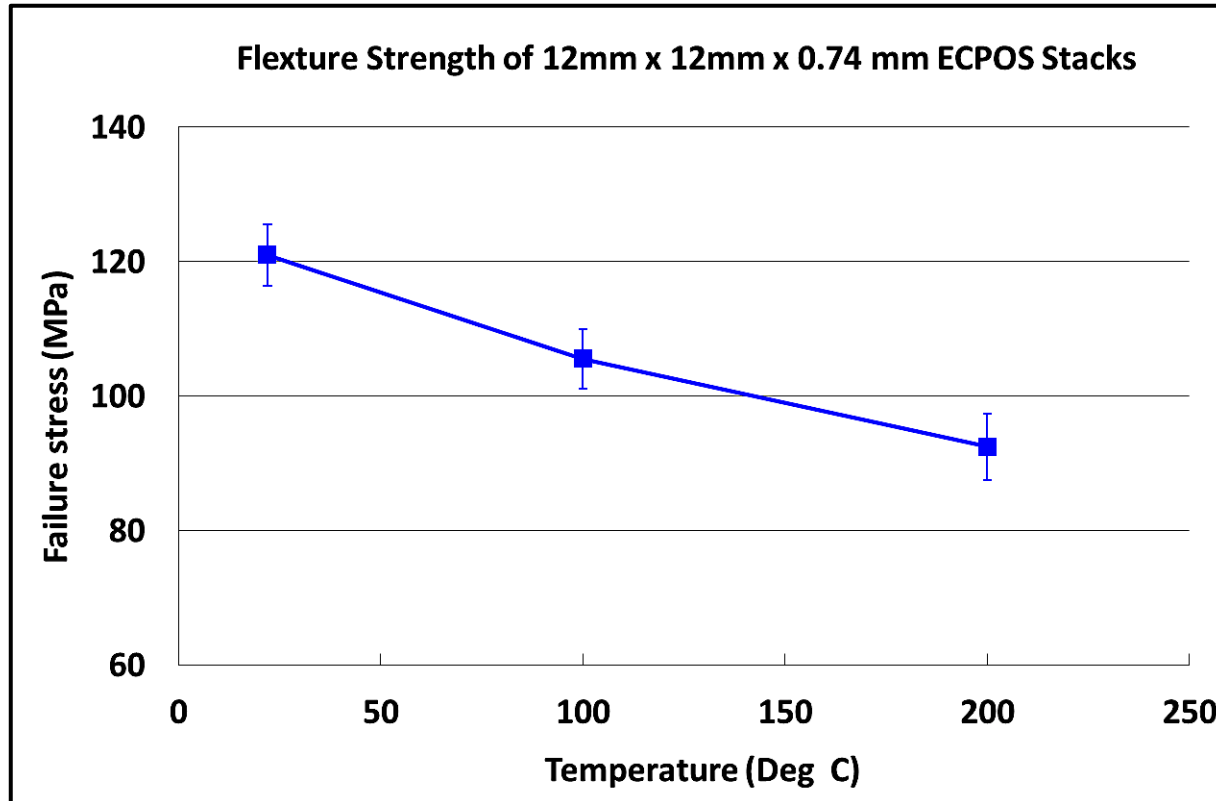


BoR setup with specimen
and ball loaded

- Triple alumina tubes with a protruded edge of 9.5mm served as a supporting ring, and f19.05mm alumina sphere used as the loading ball.
- High temperature tests were carried out using:
 - A 20 minute soak-time
 - Loading Rate: 0.001mm/s

Accomplishments (continued)

Mechanical Strength of PZT Exhibited 25% Decrease from RT to 200°C

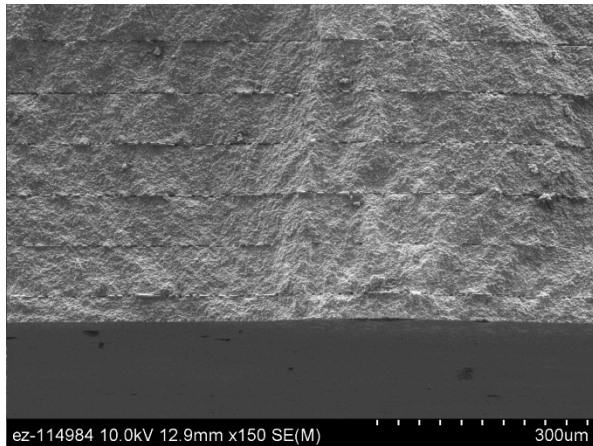


**EPCOS 10-layer stacks were used (provided by Cummins);
three temperatures were tested each 24 specimens.**

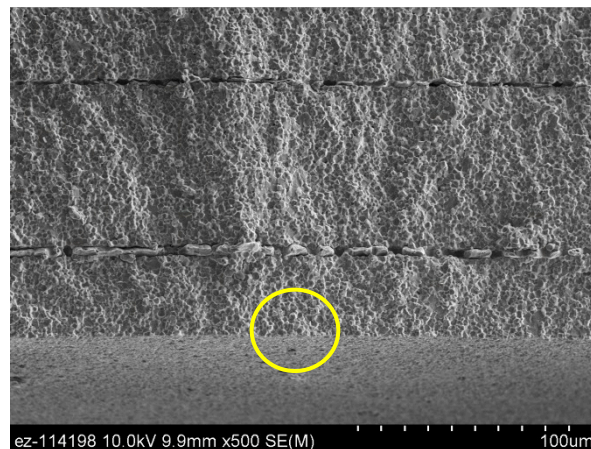
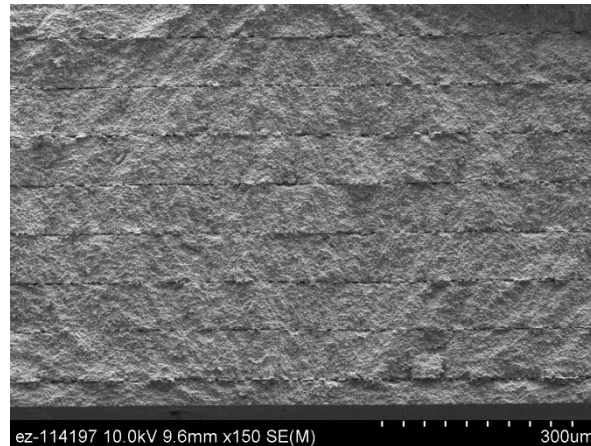
Accomplishments (continued)

PZT Strength Limited by Surface-Located Processing Agglomerates

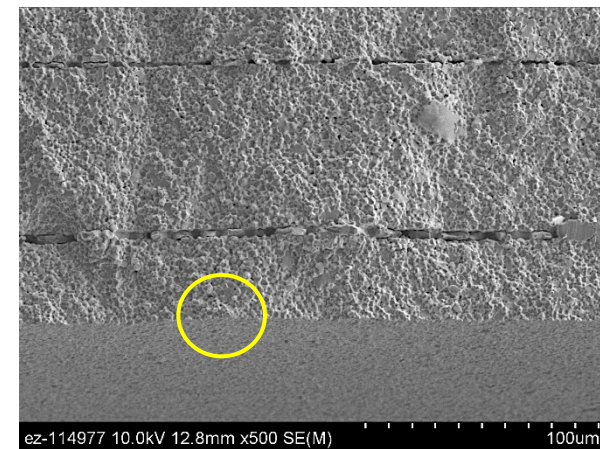
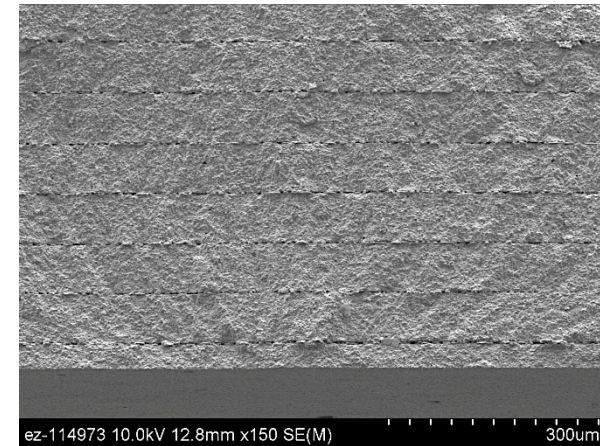
RT



100°C

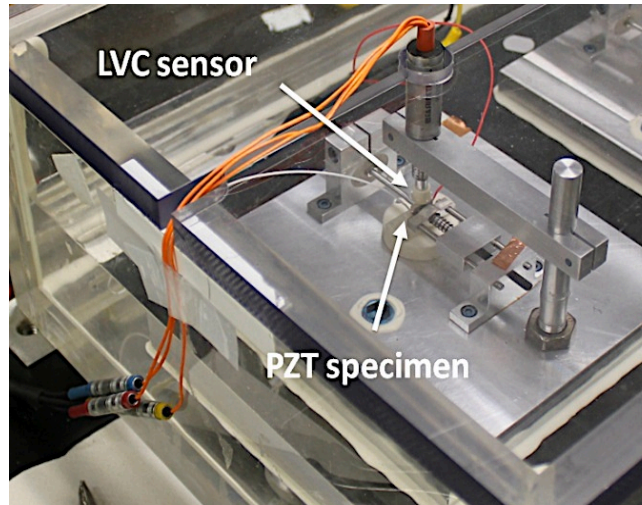
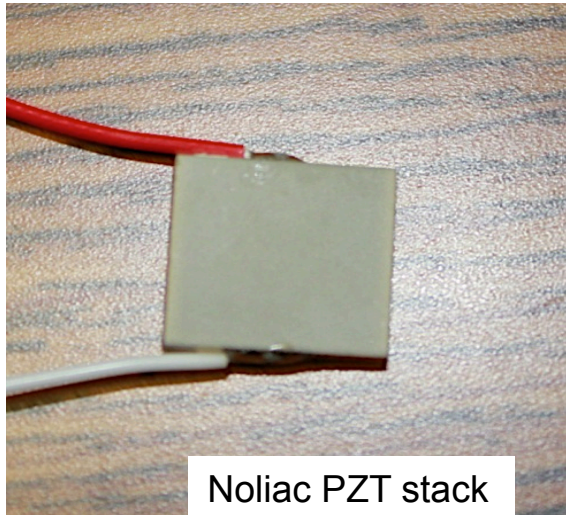


200°C



Accomplishments (continued)

Piezodilatometer Developed at ORNL to Characterize PZT Stack Electric Fatigue

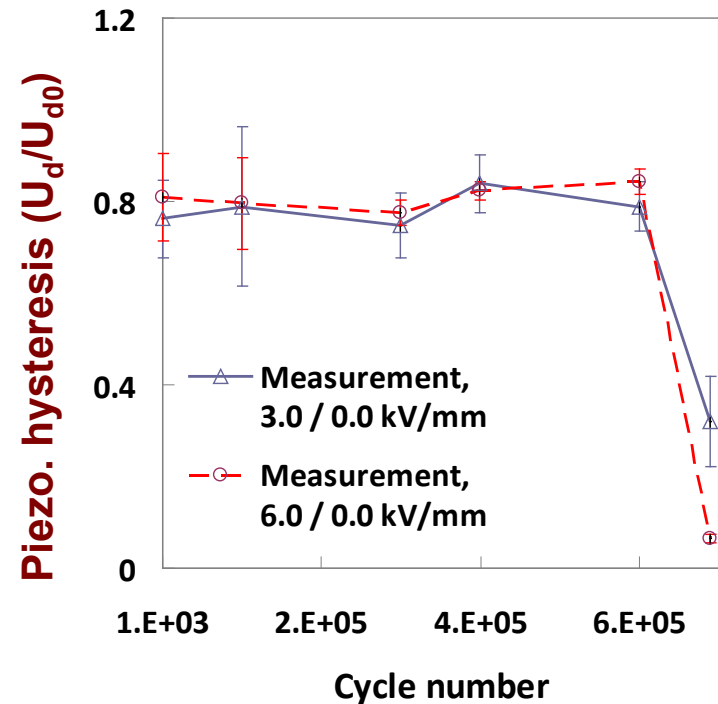
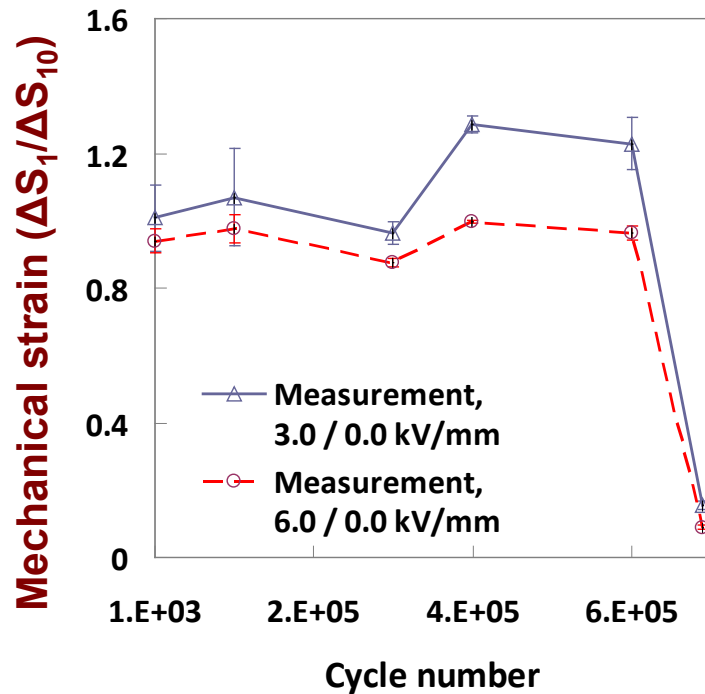


*Piezodilatometer
developed by
ORNL*

- Noliac stack CMAP09 is selected: 10x10x2mm, 400 nF, 200V
- New HV amplifier (Trek PZD2000A) enables cycle test; : +/-2kV, +/-400mA.
- FC-40 dielectric fluid is used to suppress the dielectric breakdown.

Accomplishments (continued)

Significant Reductions in Both Mechanical Strain and Piezoelectric Hysteresis Were Observed

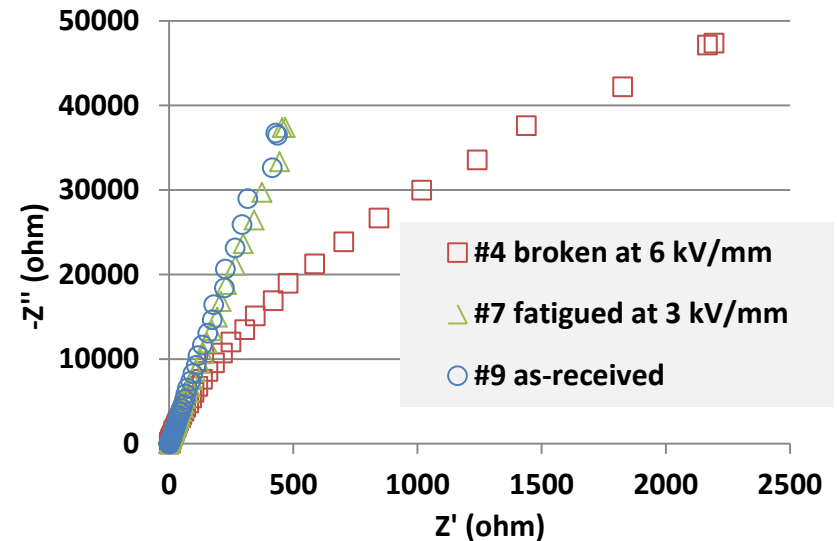
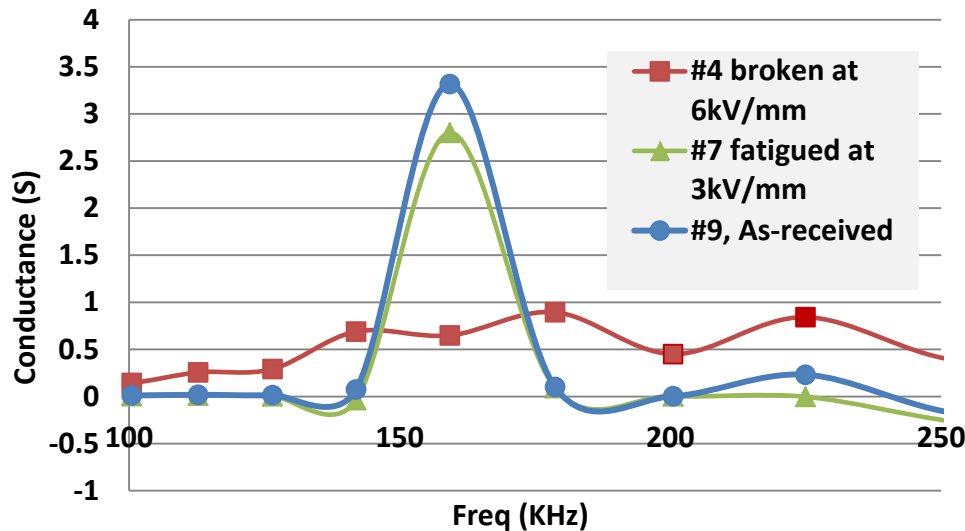


- Specimens cycled under 100 Hz unipolar sine wave with 6 kV/mm.
- The results are averaged using 3-5 specimens.

Accomplishments (continued)

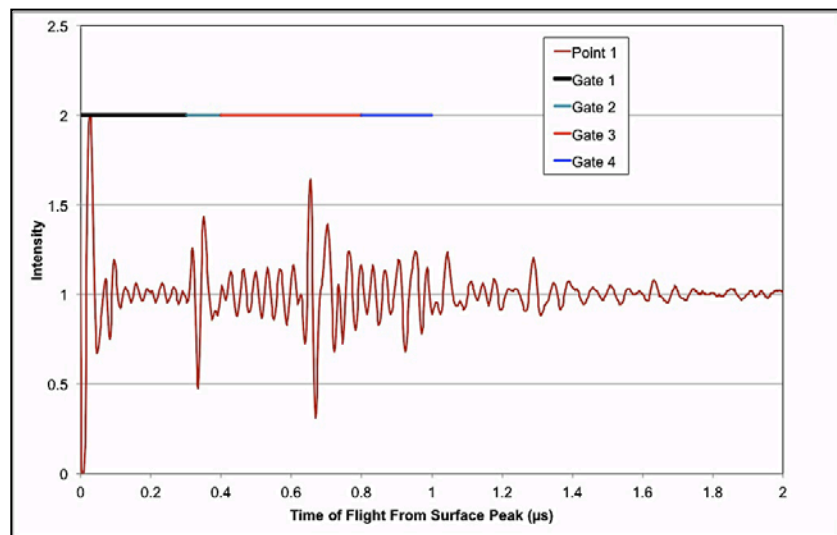
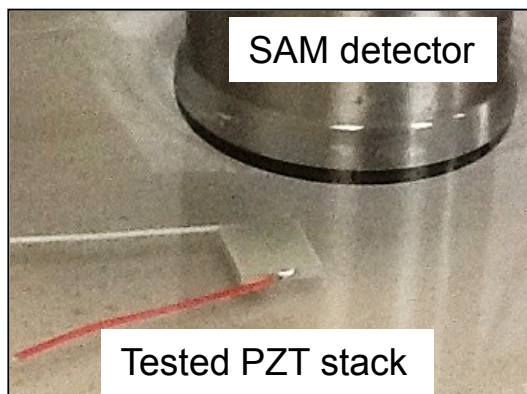
Electric impedance analysis was identified as a potential health monitoring diagnostic tool

- Impedance analysis has been incorporated into the evaluation of PZT stack during the electric cycle tests.
- Conductance spectrum and Z-plot of PZT stacks revealed distinct difference among various states.



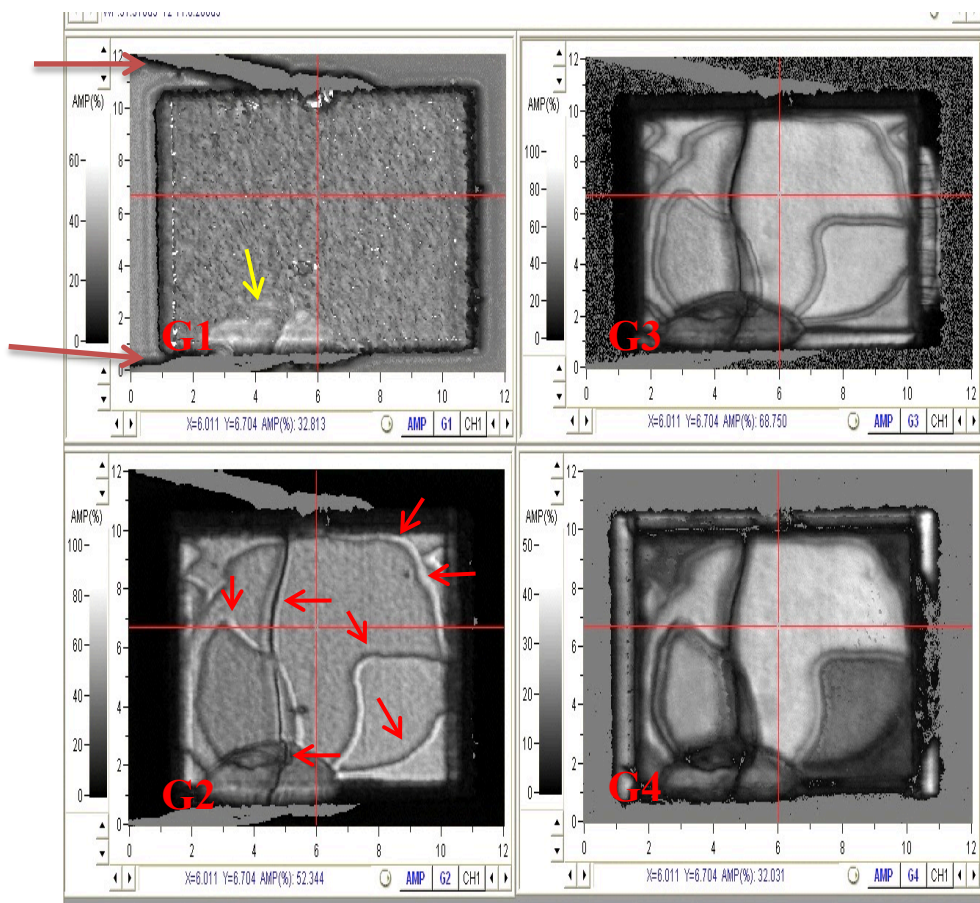
Accomplishments (continued)

Scanning Acoustic Microscopy (SAM) Useful to Image Damages in PZT Stacks



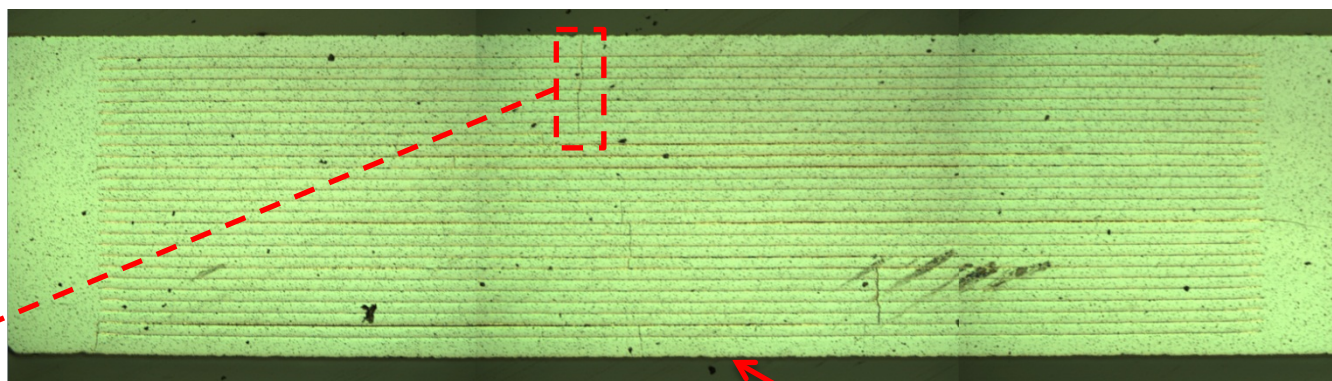
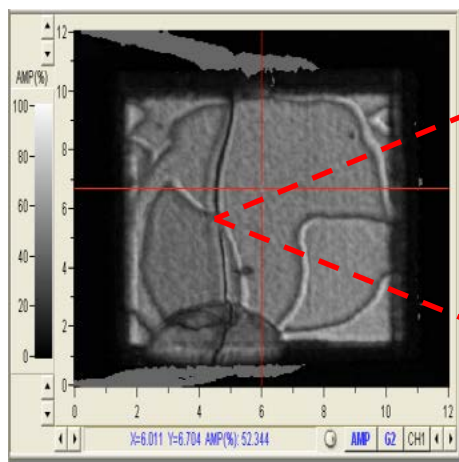
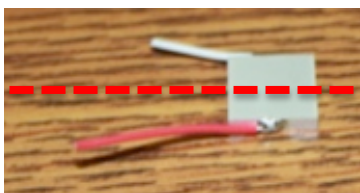
White
wire

Red
wire

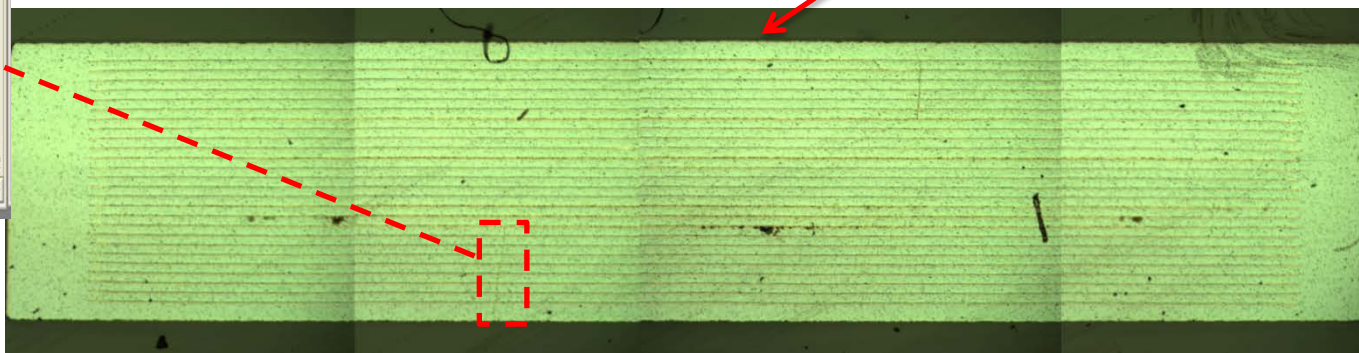


Accomplishments (continued)

Scanning Electron Microscopy Observations Confirmed the Non-Destructive SAM Evaluation

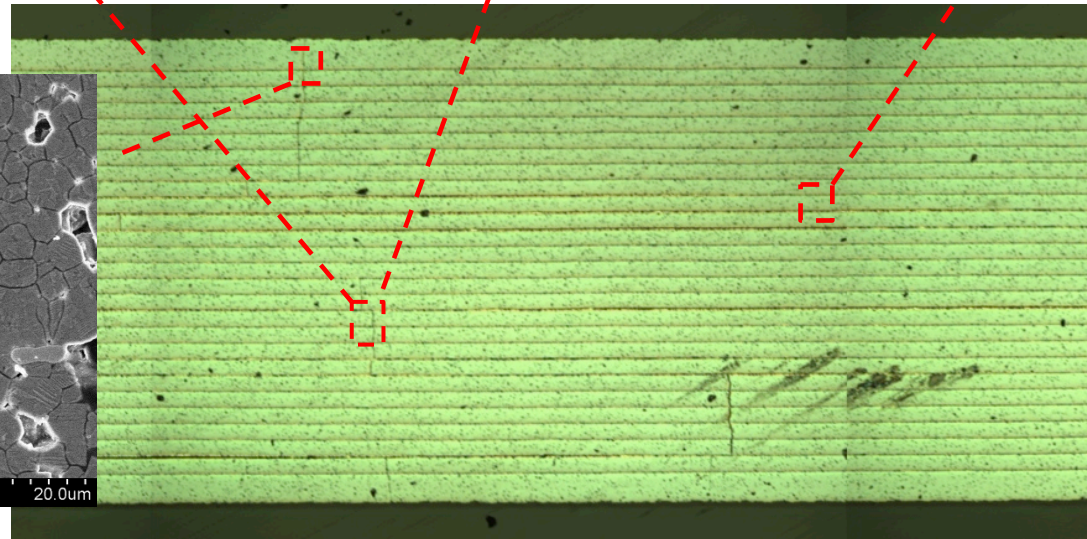
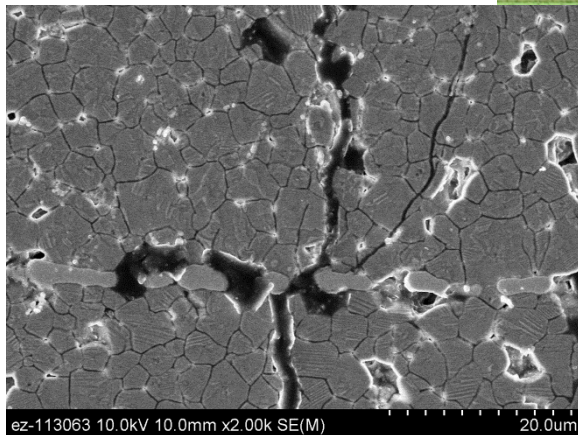
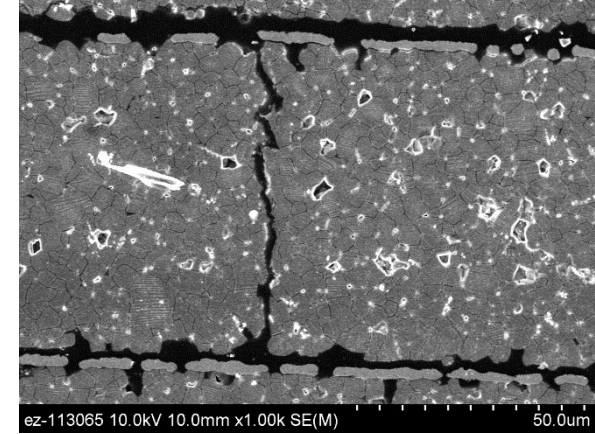
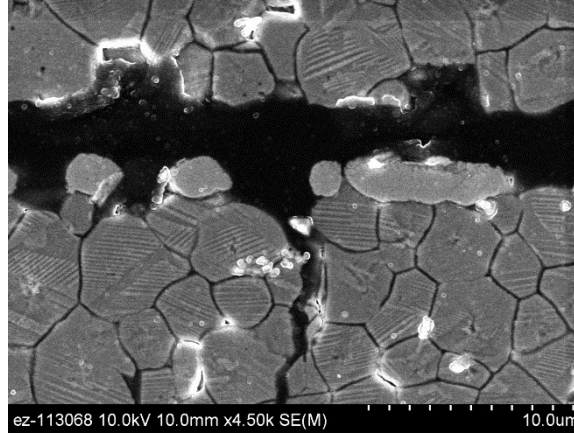
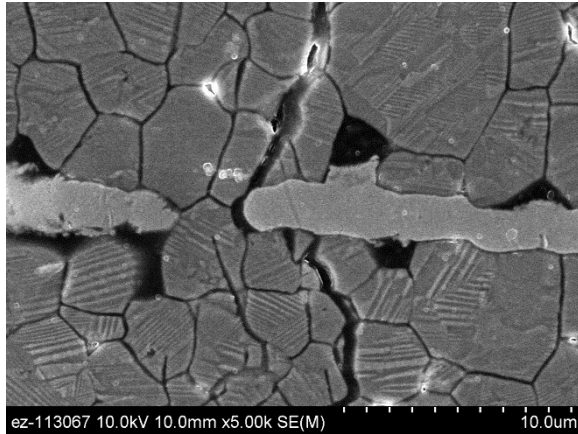


Bottom of stack



Accomplishments (continued)

**Extensive Cracks, Pores and Delaminations
Were Revealed in Failed Stack**



Collaborations

➤ Partners

- ✓ **Cummins:** an ORNL-Cummins CRADA on “Design Optimization of Piezoceramic Multilayer Actuators for Heavy Duty Diesel Engine Fuel Injectors” was officially executed Oct. 2008. It will end Sept. 2014.
- ✓ **EPCOS:** collaborations to systematically manufacture the PZT ceramic specimens and stacks needed to understand the effect of material processing and test conditions on the component degradation processes.

➤ Technology transfer

- ✓ **HDD fuel injector** will be designed and commercialized by Cummins Inc.
- ✓ **CRADA with Cummins Inc.** facilitates the optimization of PZT stacks for HDD fuel injector to achieve 55% engine thermal efficiency by 2018.
- ✓ **Collaborations with EPCOS** provides key inputs to the PZT material suppliers to optimize the PZT process and stack component design to improve the long-term reliability of PZT actuators.

Future Work

- **Perform fatigue tests and update database for down-selected candidate EPCOS piezoceramics and PZT stacks of Cummins, Inc.**
- **Study piezoelectric and mechanical reliability of PZT with emphasis on humidity and temperature effects.**
- **Evaluate accelerated electric fatigue response of PZT multilayer actuator fabricated via tape-cast process.**
- **Fabricated additional PZT stack fatigue test frame with controlled environment.**
- **Use probability design sensitivity analysis with FEA to identify optimum design of PZT multilayer actuator.**

Summary

- **Relevance:** PZT ceramic actuator provides key technology to improve fuel efficiency and reduce emission of HDD engine
- **Approach:** measure and characterize PZT ceramics and stacks under electric fatigue and controlled environment
- **Collaborations:** Cummins (HDD engine) and EPCOS (PZT supplier)
- **Technical Accomplishments:**
 - ✓ Completed the humidity study on mechanical strength of the poled PZT under various electric conditions.
 - ✓ Completed strength testing as a function of temperature.
 - ✓ Completed electric cycle test method of PZT stacks at high electric field levels by using piezodilatometer.
 - ✓ Identified electrical impedance as an important online diagnostic tool for health monitoring of PZT stack performance.
- **Future work:**
 - ✓ Evaluate mechanical performance of PZT ceramics under combined temperature, humidity, and electric field
 - ✓ Electric cycle fatigue tests on PZT stacks under simulated application environments
 - ✓ Optimum design of PZT multilayer actuator using probabilistic component design